IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received March 29, 2020, accepted April 21, 2020, date of publication April 28, 2020, date of current version May 14, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2991102

High-Power Wire Bonded GaN Rectifier for Wireless Power Transmission

SUMIN DAVID JOSEPH[1], SHAWN S. H. HSU[2], (Senior Member, IEEE), AHMED ALIELDIN[1], (Member, IEEE), CHAOYUN SONG[1], (Member, IEEE), YEKE LIU[2], AND YI HUANG[1], (Senior Member, IEEE)
[1]Department of Electrical and Electronics, University of Liverpool, Liverpool L69 3GJ, U.K.
[2]Department of Electrical Engineering, National Tsing Hua University, Hsinchu 30013, Taiwan

Corresponding authors: Shawn S. H. Hsu (shhsu@ee.nthu.edu.tw) and Yi Huang (yi.huang@liverpool.ac.uk)

ABSTRACT A novel wire bonded GaN rectifier for high-power wireless power transfer (WPT) applications is proposed. The low breakdown voltage in silicon Schottky diodes limits the high-power operations of microwave rectifier. The proposed microwave rectifier consists of a high breakdown voltage GaN rectifying element for high-power operation and a novel low loss impedance matching technique for high efficiency performance. Wire bonding method is adopted to provide electrical connection between GaN chip and board which induces undesirable inductance. In order to realize high efficiency performance, an impedance matching network is proposed to exploit the unavoidable inductance along with a single shunt capacitor, resulting in a low loss matching circuit to achieve a compact high-power rectifier. The fabricated GaN rectifier exhibits a good performance in the high-power region and can withstand up to 39 dBm input power before reaching the breakdown limit at the operating frequency of 0.915 GHz and load resistance of 100 Ω. It has a compact size and exhibits high efficiency performance in high-power region (achieved a maximum efficiency of 61.2% at 39 dBm), making it suitable for high-power applications like future unmanned intelligent devices and WPT in space applications.

INDEX TERMS GaN, high-power rectifier, microwave rectifier, rectenna, wire bonding, wireless power transfer (WPT).

I. INTRODUCTION

Wireless power transmission has gained much attention in the last few years, due to new charging requirements and the rapid advancement of electronic devices and sensor nodes [1]. Highly efficient non-radiative near field techniques are broadly accepted by industry for wireless power transfer in a limited distance with large coils [2]. However, radiative microwave power transmission is becoming a promising technology for remotely powering devices which are not easily accessible over a long distance [3]. Forthcoming unmanned and intelligent devices demand a wireless power technique to supply actuators or wireless sensors [4]. Input power required for these electronic devices is in the range of watts instead of micro and milliwatts for IoT sensors. Power transmission for low power IoT sensors (−20 to 20 dBm) are extensively studied and demonstrated in literatures using Si and GaAs commercial Schottky diodes [5]. But very few studies have been reported on the wireless power transmission for high-power applications. Therefore, in order to ensure the reliability of high-power WPT and to handle large quantity of power, a high-power microwave rectifier is an essential circuit element.

A conventional microwave rectifier mainly consists of rectifying elements, impedance matching network, DC pass filter and load resistor [6]. Rectifying elements are usually arranged in single series, shunt, voltage doubler or bridge configurations [7]. Efficiency of the microwave rectifier primarily depends on the rectifying element and the impedance matching network. Conventional rectifier usually utilize Si based Schottky diodes for rectification. Conversion efficiency in high-power region is restricted by the low breakdown voltage in silicon Schottky diodes [8]. Large voltage and current swings arise in Schottky diodes due to the high RF (radio frequency) input power. This triggers a breakdown in the metal-semiconductor junction and can permanently

The associate editor coordinating the review of this manuscript and approving it for publication was Tariq Masood.

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

damage a diode. Thus, Si Schottky diode-based rectifiers usually operate below watt-level input power.

In order to prevent the breakdown in low-power capability diodes for realizing high-power rectifiers, power divider circuits are utilized to split the high input power into several diode circuits [9]. In [10], a stepped impedance transformer and coupled lines are employed to develop a planar Wilkinson power divider. However, these circuits based on transmission lines are complex in structure and large in size. To solve the low breakdown voltage problem of the Schottky diodes in the zero-bias and full-wave bridge rectifiers, the one-to-four series-dividing transformer and parallel-dividing transformer for impedance matching and power dividing are employed in [11]. Diode arrays were also used to increase the power capacity of microwave rectifiers [12]. However, these approaches introduce additional size and losses, as well as increase circuit complexity.

In this paper, a GaN Schottky diode based high-power microwave rectifier is proposed. High current carrying ability of GaN is utilized to realize the rectifier. A GaN HEMT is turned to a Schottky diode by shorting the source and drain to make the cathode and gate as the anode. Circuit model of GaN diode is estimated for better simulation of the rectifier. A shunt diode topology is adopted in this high-power rectifier to achieve maximum efficiency. Impedance matching is achieved in this rectifier by using a single shunt capacitor along with the bond-wire interconnects. The length of interconnects is properly designed to attain the impedance matching with minimum number of lumped elements, to minimize the losses. Due to the low loss rectifying element and efficient impedance matching technique, the high-power GaN rectifier achieves a peak efficiency of 61.2 % at 39 dBm. Maximum output voltage of 24.5 V is observed at 0.915 GHz with an input power of 40 dBm.

The organization of this paper as follows. The rectifying element selection, wire bonding interconnects and the rectifier design are presented in Section II. The proposed high-power rectifier performance is illustrated and discussed in Section III. Comparison with related high-power rectifiers are also presented in this section. Finally, conclusions are drawn in Section IV.

II. RECTIFIER DESIGN

A. RECTIFYING ELEMENT SELECTION

The difficulty in development of high-power rectifier is the limitations of the performance of the rectifying element. A high breakdown voltage and current carrying capabilities of the rectifying element are necessary factors in the design of a high-power rectifier. Parameters of commercially available diodes are summarized in Table 1 for comparison. It can be observed that Si and GaAs based commercially available diodes has low reverse breakdown voltage (≤15 V) and power capabilities, which limits their applicability in high-power applications.

A promising solution to design the high-power rectifier is to use GaN technology. GaN has attracted much attention as a material suitable for operating at microwave frequencies due to the high-power and high conversion efficiency of high-power amplifiers (HPAs) and rectifiers [13]. Properties like wide bandgap, high electron saturation velocity, high critical electric field, and high carrier density in 2-D electron gas (2DEG) channel in the device and high breakdown voltage making it suitable for wireless power transmission applications [14]. GaN Schottky barrier is better suited than Si and GaAs Schottky diodes for increasing the handling power of the high-power wireless transmission.

TABLE 1. Parameters of commercially available Schottky diodes.

Diode (Company)	Technology	Breakdown voltage (V)
HSMS2862 (Avago)	Si	7
DMK2790 (Skyworks)	GaAs	4
MA4E1317(MACOM)	GaAs	7
HSMS270B (Avago)	Si	15

Based on the above-mentioned properties, a GaN HEMT is proposed for wireless power transfer application. A Schottky barrier diode is implemented by shorting the source and drain of the HEMT to serve as the cathode. Layout of the GaN HEMT is shown in Fig. 1. To design the rectifier circuit, the GaN Schottky diode is measured individually to achieve the diode model for ADS simulation. I-V (current-voltage) and C-V (capacitance-voltage) measurements are carried out and curve fitting is performed for estimating the diode parameters. Circuit model of the GaN diode is shown in Fig. 2. The measured breakdown voltage of the GaN diode Bv is 76 V, which makes it suitable for high-power applications. Due to the large bandgap of GaN material, forward voltage Vf is observed as 1.1 V. Instead of using GaN, a low forward voltage of Si Schottky diodes with similar series resistance and breakdown voltage can only perform at low frequencies. Due to the larger size of the pads in the GaN chip, the parasitic elements have high values. However, proper impedance matching can cancel out the reactive parasitic elements of the physical diode without affecting the rectifying efficiency.

B. WIRE BONDNG INTERCONNECTS

For realizing a high-power and high efficiency rectifier, it is necessary to eliminate the packaging losses of the semiconductor devices. Therefore, a chip on board method is adopted in this design by directly using the GaN chip in the rectifier circuit. Chip on board method helps to eliminate the packaging of semiconductor devices and thus, the final product can be more compact, lighter, and less costly.

Flip-chip and wire bonding are widely adopted techniques to interconnect chip and PCB board [15]. In flip-chip method, small solder bumps are employed in PCB board. Then the chip is inverted so that the metallized side facing the circuit

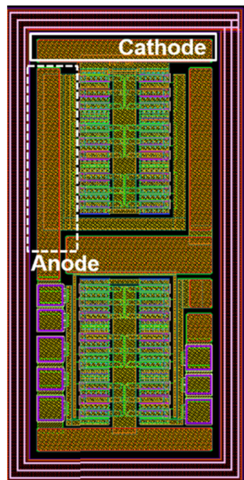

FIGURE 1. Layout of GaN HEMT.

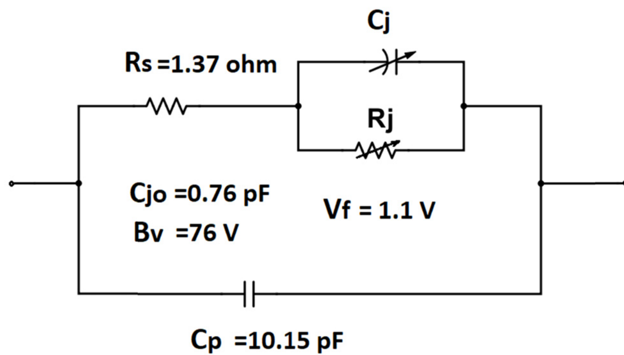

FIGURE 2. Circuit model of GaN Schottky diode.

board. Electrical connection is realized by reflow soldering process. Flip chip interconnects offer lower inductance however have some drawbacks including poor thermal dissipation to the PCB, and electromagnetic coupling to the PCB that may not have been taken into account during the chip design. In wire bonding, a small wire lead is used to connect the chip and board. This process is quite similar to the way that an integrated circuit is connected to its lead frame, but instead the chip is directly connected to circuit board. For higher frequencies this interconnect leads to higher inductance values which makes the impedance matching difficult [16]. In this GaN rectenna design, wire bond interconnection is employed for connecting GaN chip on the circuit board.

Wire bonding interconnect can be modeled by using an equivalent circuit as shown in Fig. 3. Equivalent circuit mainly consists of a series inductance (L_w) and series resistance (R_w). Input and output capacitances (C_w) depict the electrical representation for the coupling to the substrate. As the operating frequency of the proposed design is 0.915 GHz, the major factor is the series inductance. In order to gain a better understand of bond wire, the performance of the bond wire is analyzed using ADS software. Diameter of the bond wires in this design is considered as 30 um. Fig. 4 illustrates the variation in inductance and resistance value

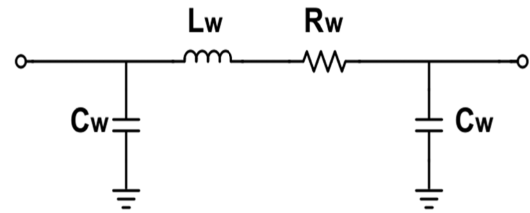

FIGURE 3. Equivalent circuit of wire bonding.

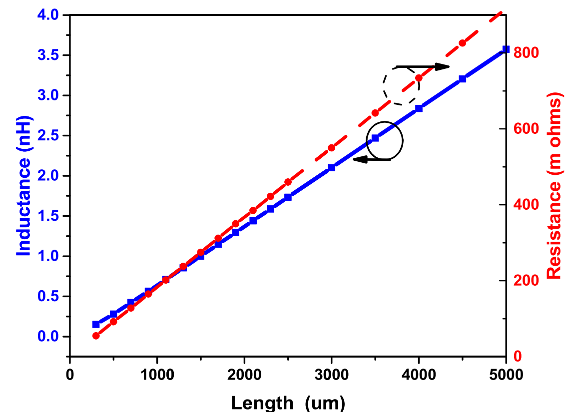

FIGURE 4. Inductance (Lw) and resistance (Rw) versus bond wire length.

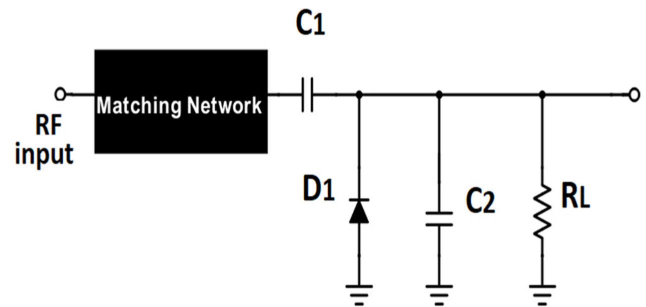

FIGURE 5. Conventional shunt diode rectifier.

with respect to the bond wire length. It can be observed that the length of the bond wire is proportional to the inductance and resistance. Inductance is varying from 0.15 to 3.57 nH at 0.915 GHz whereas resistance varies from 0.055 to 0.9 ohms by changing bond wire length from 250 um to 5000 um. The effect of input and output bond wire capacitance is considerably negligible at this frequency.

C. IMPEDANCE MATCHING AND RECTIFIER DESIGN

The topology of the rectifier is a crucial factor in determining the output power and efficiency of a rectifier. For maximum conversion efficiency, a shunt diode topology is selected in this design. A conventional shunt diode configuration is depicted in Fig. 5.

RF power is initially passed through a matching network for delivering the maximum power. The negative half cycle of the wave is rectified by the shunt diode D_1 and the energy is stored in C_1. C_2 along with load resistor R_L acts as a DC pass filter to suppress the ripples from the rectified voltage.

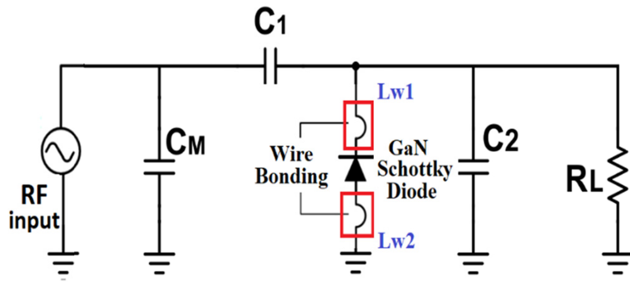

FIGURE 6. Proposed high-power GaN rectifier.

The impedance matching section in a rectifier has an important role in determining the losses of a rectifier. Due to the non-linearity of the Schottky diode, complex impedance matching circuits with lumped elements may act as the main source of loss and could affect the rectifier performance. To implement a high-power rectenna with high efficiency, it is necessary to reduce the losses accompanying the matching network as low as possible. Therefore, designing the impedance matching network with minimum components is essential to realize a high efficiency rectifier.

For providing the electrical connection between chip and circuit board, wire bond is necessary. Hence, the proposed solution is to exploit the undesirable inductance effects of wire bonding in order to ease the impedance matching process. By properly estimating the length required for impedance matching, it is possible to avoid other lossy lumped inductors. Therefore, the unavoidable interconnecting bond wires for GaN chip can be effectively use with a capacitor for impedance matching.

The schematic of the proposed high-power rectifier with a wire-bonding-based impedance matching network is shown in Fig. 6. The circuit includes the rectifying GaN HEMT based diode, matching capacitor C_M, energy storage element C_1, bond wires for attaching the chip to PCB, DC pass filter using capacitor C_2 and output load resistor. Instead of the conventional T-shaped or π-shaped impedance matching networks, a single shunt capacitor C_M is used in this proposed high-power rectifier along with the wire bonds for interconnection. L_{W1} and L_{W2} represents the length of wire bonds used for interconnection of GaN chip in circuit and also serves as inductors for impedance matching. For wireless energy harvesting applications, the expected RF input power from the antenna is in the range of 0 dBm (i.e., 1 mW). But in this design as we are aiming for high-power operation of rectifier, the rectifier is designed to perform well in the high-power region of 20 to 40 dBm. So, the designed high-power rectenna should have a maximum efficiency in this range of input power. Fig. 7 represents the impedance tuning by employing shunt capacitor and bond wire length, L ($L = L_{W1} = L_{W2}$). It can be observed that by varying the capacitor value with accordance to the length of the wire bonds, it is possible to match the impedance properly at different frequencies. Therefore, the length of wire bond is taken as 900 um.

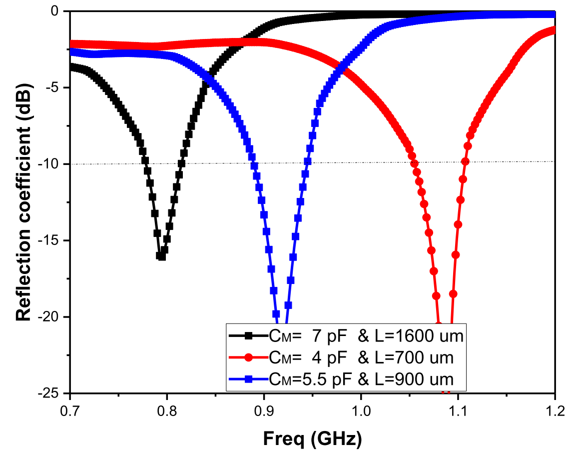

FIGURE 7. Impedance tuning by shunt capacitor and bond wire.

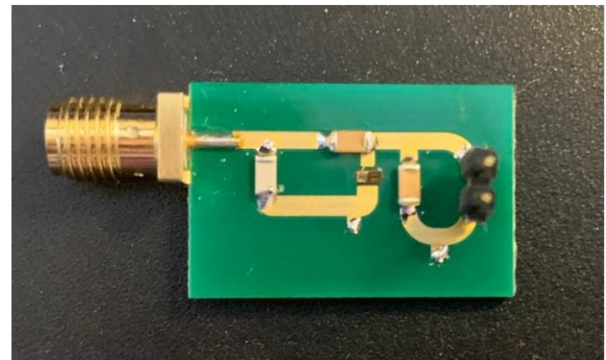

FIGURE 8. Fabricated high-power GaN rectifier.

The proposed single shunt high-power rectifier is designed at 0.915 GHz on a 1.6 mm thick FR4 substrate ($\varepsilon r = 4.4$, tan $\delta = 0.02$). Rectifier layout is optimized to deliver maximum output DC power in the above-mentioned received antenna power. The final values of C_M and R_L have been determined through an optimization process performed with the commercial software Agilent ADS; both circuit analysis and full electromagnetic simulations have been carried out for improving results reliability. The load resistor value is selected based on the required DC voltage at the output of the rectifier. While designing the rectifier, the maximum conversion efficiency and maximum output DC power are enhanced based on the value of the load resistor. A 100 Ω resistor is selected as the load after careful design simulations. Final capacitors C_M, C_1 and C_2 are 5.1, 10000 and 10000 pF respectively (Murata components have been used).

III. RECTIFIER PERFORMANCE

The proposed microwave rectifier has been made and evaluated using the measurement setup shown in Fig. 9. A Keithley 2920 RF signal generator with an output power up to 13 dBm has been utilized to generate the RF signal at 0.915 GHz. A 40 dB power amplifier has been employed to amplify the signals for the testing of high-power rectifier. To protect the signal generator from any power surge and reflections,

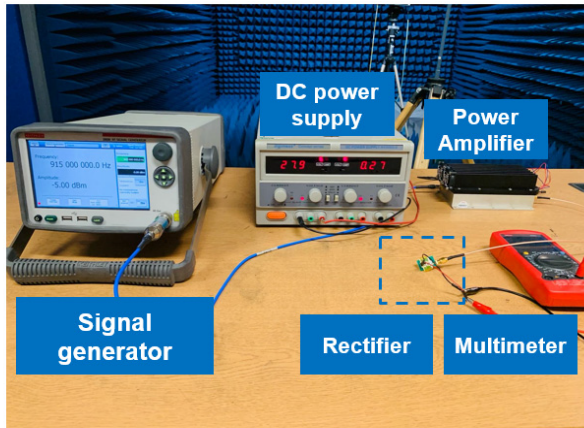

FIGURE 9. Measurement setup of high-power GaN rectifier.

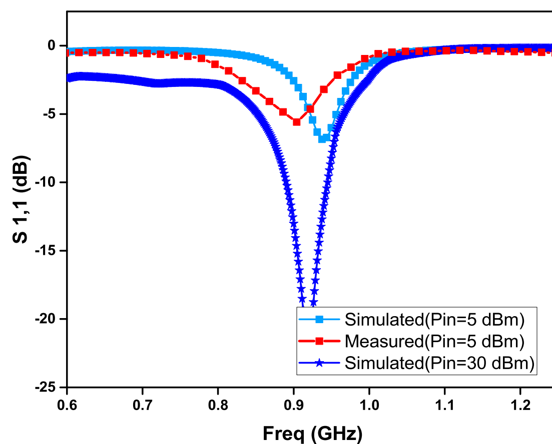

FIGURE 10. Simulated and measured S1,1 of high-power GaN rectifier.

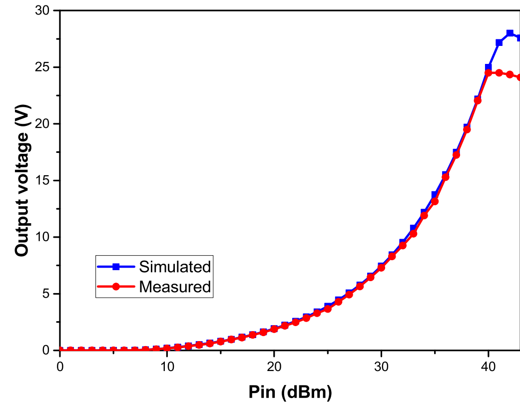

FIGURE 11. Simulated and measured output voltage of high-power GaN rectifier.

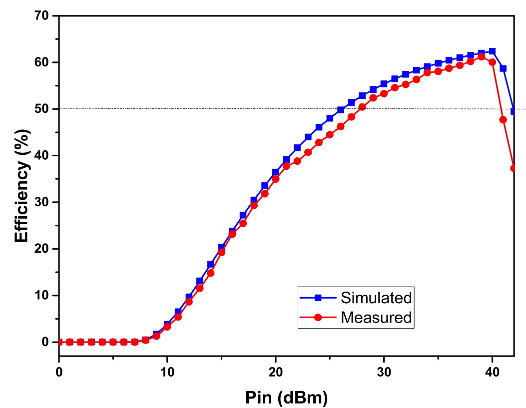

FIGURE 12. Simulated and measured conversion efficiency of high-power GaN rectifier.

a 3-dB attenuator is connected between the signal generator and power amplifier. For analyzing and estimating the signal power from the power amplifier a Keithley signal analyzer together with a 20-dB attenuator is utilized. A digital multimeter has been used to measure the output voltage across the R_L resistor. The measurement setup has been appropriately calibrated considering all device losses to provide the most reliable results. Fig. 10 shows simulated and measured S-parameter of the designed high-power rectifier. Acceptable matching condition was confirmed under large signal S-parameters (LSSP) in the range of 30-40 dBm input power. Measured S parameter has a good agreement with simulated value at 5 dBm input power.

Fig. 11 shows the simulated and measured output DC voltage of the GaN rectifier. It can be observed that a maximum voltage of 24.5 V is obtained at 40 dBm input power. Measured output voltage has good agreement with simulated values. The input power to the rectifier has been varied from 0 to 43 dBm, to measure the DC voltage across the load resistor. Input power is restricted to 43 dBm in order to ensure the safe operation of GaN rectifier. The RF-to-DC conversion efficiency (η) of a microwave rectifier is calculated as the ratio of the rectified DC output power to the incident RF power, and it can be expressed as

$$\eta = V_{out}^2 \Big/ R_L P_{in} \times 100\% \tag{1}$$

where P_{in} is the input power and V_{out} is the DC output voltage across the load resistor R_L of the microwave rectifier. Fig. 12 shows the simulated and measured conversion efficiencies of the proposed microwave rectifier as a function of input power. Maximum measured efficiency of 61.2 % is observed at 39 dBm. Efficiency is more than 50% from an input power of 28 dBm. A comparison between the proposed GaN rectifier and other relevant high-power rectifiers is given in Table 2.

The proposed GaN rectifier design has achieved high output power with high efficiency. It can be observed that our design can stand high input power of 39 dBm compared to the other published designs. Although the measured results have shown that the proposed rectifier has a high output power, the overall dimension of our design is still the lowest due to the absence of complex and large matching networks. The proposed high-power rectifier is better than the other published designs in terms of the overall performance and compact size due to the novel wire bond matching, and thus is a very good candidate for future unmanned WPT applications.

TABLE 2. Comparison of the proposed rectifier with related rectifiers.

Design	[17]	[4]	[18]	[19]	[20]	This work
Frequency (GHz)	0.915	2.45	0.915	2.45	0.915	**0.915**
Input power (dBm)	22	34	29	19	16	**39**
V_{out} (V)	4	15	-	5.2	5.5	**22.05**
Size (mm^2)	31 × 15.6 ($0.1\lambda_0 \times 0.05\lambda_0$)	24 × 35 ($0.20\lambda_0 \times 0.29\lambda_0$)	-	90 × 50 ($0.74\lambda_0 \times 0.41\lambda_0$)	23 × 37 ($0.07\lambda_0 \times 0.11\lambda_0$)	**16 × 22 ($0.05\lambda_0 \times 0.07\lambda_0$)**
Rectifying element	HSMS2850 and HSMS2860	HSMS 270 B	HSMS2822 and HSMS2852	HSMS 2862	HSMS2850 and GaAs pHEMT	**GaN**
Matching elements	FET transistor and microstrip lines	Three sections of microstrip lines	Microstrip lines	Double branch matching	Microstrip lines	**Single capacitor and bond wires**
Output power (Watts)	0.123	1.95	0.53	0.06	0.02	**4.9**

IV. CONCLUSION

In this paper, a novel high efficiency GaN rectifier for high-power WPT applications has been proposed. In order to realize high-power operations, a high breakdown voltage GaN Schottky diode is implemented from GaN HEMT. Chip on board technique is utilized to avoid the packaging losses and to reduce the size. A novel low loss impedance matching is proposed by exploiting the unavoidable inductance effects of bond wires used for providing the electrical connection between GaN chip and board. The microwave rectifier has been optimized for 0.915 GHz frequency and an input power of 39 dBm. The fabricated GaN rectifier achieved a maximum efficiency of 61.2% and a high output voltage of 22.05 V has been achieved at this optimized input power of 39 dBm. The proposed rectenna is better than the other published designs in terms of the high-power operation as well as the peak voltage and power. The fabricated prototype has a compact size and exhibits high efficiency performance in high-power region, making it a good candidate for high-power electronics like future unmanned intelligent devices.

REFERENCES

[1] M. Tabesh, N. Dolatsha, A. Arbabian, and A. M. Niknejad, "A power-harvesting pad-less millimeter-sized radio," *IEEE J. Solid-State Circuits*, vol. 50, no. 4, pp. 962–977, Apr. 2015.

[2] A. P. Sample, D. A. Meyer, and J. R. Smith, "Analysis, experimental results, and range adaptation of magnetically coupled resonators for wireless power transfer," *IEEE Trans. Ind. Electron.*, vol. 58, no. 2, pp. 544–554, Feb. 2011.

[3] S. Ladan, A. B. Guntupalli, and K. Wu, "A high-efficiency 24 GHz rectenna development towards millimeter-wave energy harvesting and wireless power transmission," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 61, no. 12, pp. 3358–3366, Dec. 2014.

[4] F. Zhao, Z. Li, G. Wen, J. Li, D. Inserra, and Y. Huang, "A compact high-efficiency watt-level microwave rectifier with a novel harmonic termination network," *IEEE Microw. Wireless Compon. Lett.*, vol. 29, no. 6, pp. 418–420, Jun. 2019.

[5] C. Song, Y. Huang, P. Carter, J. Zhou, S. D. Joseph, and G. Li, "Novel compact and broadband frequency-selectable rectennas for a wide input-power and load impedance range," *IEEE Trans. Antennas Propag.*, vol. 66, no. 7, pp. 3306–3316, Jul. 2018.

[6] C. Song, Y. Huang, J. Zhou, J. Zhang, S. Yuan, and P. Carter, "A high-efficiency broadband rectenna for ambient wireless energy harvesting," *IEEE Trans. Antennas Propag.*, vol. 63, no. 8, pp. 3486–3495, Aug. 2015.

[7] T. Mitani, S. Kawashima, and T. Nishimura, "Analysis of voltage doubler behavior of 2.45-GHz voltage doubler-type rectenna," *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 4, pp. 1051–1057, Apr. 2017.

[8] J. Zbitou, M. Latrach, and S. Toutain, "Hybrid rectenna and monolithic integrated zero-bias microwave rectifier," *IEEE Trans. Microw. Theory Techn.*, vol. 54, no. 1, pp. 147–152, Jan. 2006.

[9] Y. Xu and R. G. Bosisio, "Design of multiway power divider by using stepped-impedance transformers," *IEEE Trans. Microw. Theory Techn.*, vol. 60, no. 9, pp. 2781–2790, Sep. 2012.

[10] S. Kim, S. Jeon, and J. Jeong, "Compact two-way and four-way power dividers using multi-conductor coupled lines," *IEEE Microw. Wireless Compon. Lett.*, vol. 21, no. 3, pp. 130–132, Mar. 2011.

[11] C.-Y. Liou, M.-L. Lee, S.-S. Huang, and S.-G. Mao, "High-power and high-efficiency RF rectifiers using series and parallel power-dividing networks and their applications to wirelessly powered devices," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 1, pp. 616–624, Jan. 2013.

[12] U. Olgun, C.-C. Chen, and J. L. Volakis, "Investigation of rectenna array configurations for enhanced RF power harvesting," *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 262–265, 2011.

[13] H. T.-A. Nia and V. Nayyeri, "A 0.85–5.4 GHz 25-W GaN power amplifier," *IEEE Microw. Wireless Compon. Lett.*, vol. 28, no. 3, pp. 251–253, Mar. 2018.

[14] A. Hassan, Y. Savaria, and M. Sawan, "GaN integration technology, an ideal candidate for high-temperature applications: A review," *IEEE Access*, vol. 6, pp. 78790–78802, 2018.

[15] T. H. Hong, J. Beleran, K. Y. S. Drake, O. P. L. Wilson, G. Mehta, G. Librado, X. R. Zhang, and C. Surasit, "Packaging approach for integrating 40/45-nm ELK devices into wire bond and flip-chip packages," *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 1, no. 12, pp. 1923–1933, Dec. 2011.

[16] L. Lin, Y.-J. Hua, L. Zhou, Q. Wu, J. Mao, and W.-Y. Yin, "Ruggedness characterization of bonding wire arrays in LDMOSFET-based power amplifiers," *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 8, no. 6, pp. 1032–1041, Jun. 2018.

[17] A. M. Almohaimeed, M. C. E. Yagoub, and R. E. Amaya, "A highly efficient power harvester with wide dynamic input power range for 900 MHz wireless power transfer applications," in *Proc. 16th Medit. Microw. Symp. (MMS)*, Abu Dhabi, United Arab Emirates, Nov. 2016, pp. 1–4.

[18] M. Huang, Y. L. Lin, J.-H. Ou, X. Y. Zhang, Q. W. Lin, W. Che, and Q. Xue, ''Single- and dual-band RF rectifiers with extended input power range using automatic impedance transforming,'' *IEEE Trans. Microw. Theory Techn.*, vol. 67, no. 5, pp. 1974–1984, May 2019.

[19] Y. Cao, W. Hong, L. Deng, S. Li, and L. Yin, ''A 2.4 GHz circular polarization rectenna with harmonic suppression for microwave power transmission,'' in *Proc. IEEE Int. Conf. Internet Things (iThings), IEEE Green Comput. Commun. (GreenCom), IEEE Cyber, Phys. Social Comput. (CPSCom), IEEE Smart Data (SmartData)*, Chengdu, China, Jul. 2016, pp. 359–363.

[20] Z. Liu, Z. Zhong, and Y.-X. Guo, ''Enhanced dual-band ambient RF energy harvesting with ultra-wide power range,'' *IEEE Microw. Wireless Compon. Lett.*, vol. 25, no. 9, pp. 630–632, Sep. 2015.

SUMIN DAVID JOSEPH received the B.Tech. degree (Hons.) in electronics and communication from the Cochin University of Science and Technology, India, in 2012, the M.Tech. degree (Hons.) in communication systems from the Visvesvaraya National Institute of Technology, India, in 2015. He is currently pursuing the dual Ph.D. degree in electrical engineering with the University of Liverpool, U.K., and National Tsing Hua University, Taiwan.

He was a Lab Engineer under CoE with the Visvesvaraya National Institute of Technology, India, where he was involved in projects of national importance. His research interests include self-biased circulators, mm-wave antenna arrays, rectifying antennas, rectifiers, wireless power transfer, and energy harvesting.

SHAWN S. H. HSU (Senior Member, IEEE) received the B.S. degree in electrical engineering from National Tsing Hua University, Hsinchu, Taiwan, in 1992, and the M.S. and Ph.D. degrees in electrical and computer engineering from the University of Michigan, Ann Arbor, MI, USA, in 1997 and 2003, respectively.

He is currently a Professor with the Department of Electrical Engineering, Institute of Electronics Engineering, National Tsing Hua University. He is involved in the design, fabrication, and the modeling of high-frequency transistors and interconnects. His current research interests also include the design of monolithic microwave integrated circuits and RF integrated circuits using Si/III–V-based technologies, heterogeneous integration using system-in-package, and three-dimensional integrated circuit technology for high-speed wireless/optical communications and power electronics applications.

AHMED ALIELDIN (Member, IEEE) received the B.Sc. degree in radar engineering from the Military Technical College, Egypt, in 2005, the M.Sc. (Eng.) degree in antenna and microwave propagation from the University of Alexandria, Egypt, in 2013, and the Ph.D. degree in antennas and electromagnetics from the University of Liverpool, U.K., in 2019.

His academic research activities and Ph.D.'s were centered on antenna designing and measurements with an emphasis on mobile communication applications. His academic research works include novel textile antennas, multiple-input multiple-output antennas, base station antennas, satellite antennas, transparent antennas, and phased-MIMO radar antennas. In addition to work in academia, he also held various positions throughout more than ten years working in the industry. He has authored/coauthored many articles in leading international journals and conference proceedings. He has also filed a patent. He serves as a technical reviewer for leading academic journals and conferences and served as the session chair for many international conferences.

CHAOYUN SONG (Member, IEEE) received the M.Sc. and Ph.D. degrees in electrical engineering and electronics from the University of Liverpool (UoL), Liverpool, U.K., in 2013 and 2017, respectively.

From 2015 to 2016, he worked as a Research Assistant with UoL, and an Antenna Design Engineer at BAE systems, Chelmsford, U.K. He is currently a Postdoctoral Research Associate within UoL. He has authored/coauthored more than 45 articles (including 20 IEEE Transactions) in internationally refereed journals and conference proceedings. He holds five U.S., EU, and U.K. patents. His current research interests include liquid antennas, novel materials, wireless energy harvesting, rectifying antennas, wireless power transfer, global navigation satellite system antennas and anti-jamming technologies, and smart sensors for the Internet of Things. He was a recipient of many international awards, such as the Winner of the IET Present Around the World Competition, in 2016, and the EW Bright-Sparks Award for outstanding electronic engineers under age 30 in the U.K., in 2018. He won the BAE Systems Chairman's Award, in 2017, for the innovation of next generation global navigation satellite system antennas. He has been a regular reviewer of more than ten international journals.

YEKE LIU was born in Nantong, Jiangsu, China, in 1993. He received the B.S. degree in measurement and control technology and equipment from Hunan University, Changsha, China, in 2015. He is currently pursuing the Ph.D. degree in electronics engineering with National Tsing Hua University, Hsinchu, Taiwan. His current research interests include the design, fabrication, and the modeling of high frequency devices using wide-bandgap materials.

YI HUANG (Senior Member, IEEE) received the B.Sc. degree in physics from Wuhan University, China, in 1984, the M.Sc. (Eng.) degree in microwave engineering from NRIET, Nanjing, China, in 1987, and the D.Phil. degree in communications from the University of Oxford, U.K., in 1994.

His experience includes three years spent with NRIET, China, as a Radar Engineer, and various periods with the Universities of Birmingham, Oxford, and Essex, U.K., as a member of Research Staff. He has been conducting research in the areas of wireless communications, applied electromagnetics, and radar and antennas, since 1987. He worked as a Research Fellow at British Telecom Labs, in 1994, and then joined the Department of Electrical Engineering and Electronics, University of Liverpool, U.K., in 1995, as a Faculty, where he is currently a Full Professor in wireless engineering, the Head of the High Frequency Engineering Group, and the Deputy Head of the Department. He has published over 350 refereed articles in leading international journals and conference proceedings, and authored *Antennas: From Theory to Practice* (John Wiley, 2008) and *Reverberation Chambers: Theory and Applications to EMC and Antenna Measurements* (John Wiley, 2016). He is a Fellow of IET and Senior Fellow of HEA. He has received many research grants from research councils, government agencies, charity, EU and industry, acted as a consultant to various companies, and served on a number of national and international technical committees and been an editor, associate editor or guest editor of five international journals. He has been a keynote/invited speaker and organizer of many conferences and workshops (e.g. WiCom 2006, 2010, IEEE iWAT2010, LAPC2012, and EuCAP2018). He is currently the Editor-in-Chief of *Wireless Engineering and Technology*, an Associate Editor of IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS, and U.K. and Ireland Rep to European Association of Antenna and Propagation (EurAAP).